MIXING AND REACTION OF PULVERIZED COAL IN AN ENTRAINED GASIFIER[1]

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INTRODUCTION

Several coal gasification processes under development include an entrained gasifier as one step in the process. In such cases, coal or char is contacted with a hot gas to cause particle combustion or gasification. Design and optimization of such units require an understanding of particle gasification kinetics, together with insight into turbulent mixing processes of the coal-laden streams with the hot gases. The present study is designed to develop an understanding of the physical and chemical rate processes that occur during gasification of entrained, pulverized coal particles.

Specific objectives are to measure locally: (1) the extent of mixing of primary and secondary gases, (2) the extent of particle dispersion, (3) the extent of particle reaction, and (4) the gaseous reaction products including pollutants. This study includes both non-reacting and reacting flow tests to be run at pressures from 1 to 20 atm. Key to the technical approach is particle and gas sampling from the reactor using water-cooled probes. Separate key components in primary and secondary streams will indicate directly the extent of gas phase mixing at the various sampling points. The particulate portion of each sample will be analyzed to determine ash, volatiles, and sulfur and nitrogen content.

TEST PROGRAM

Design of the coal gasification test program and test facility were based on review of the literature and discussions with agencies doing development work on entrained flow gasifiers. The baseline proportions of coal, oxygen and steam were determined by optimizing the theoretically computed cold gas efficiency based upon equilibrium gasification products of a typical high volatile Bituminous B coal. The baseline selected was 38 gm steam and 56 gm oxygen per 100 gm coal.

Experimental variables which were considered in establishing the test program included the particle feed rate, gas preheat temperature, primary and secondary stream velocities, secondary to primary injection angle, operating pressure, percent coal loading level, coal particle size and coal type. Table 1 summarizes the range of selected test conditions to be investigated in this study. A total of 50-60 tests are planned for the reacting test program.

TABLE 1. COAL GASIFIER TEST VARIABLES

VARIABLE	RANGE OF VARIATION
Pressure	1 - 20 atm
Coal Type	17 - 40% volatiles
Secondary Injection Angle	0 - 30°
Particle Size	30 - 60μ
Secondary Temp.	600 - 700°K
Secondary/Primary Velocity Ratio	1.25 - 2.0
Coal Feed Rate	70 - 140 kg/hr
Solids Loading	70 - 85%

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FACILITY DESIGN AND INSTALLATION

Figure 1 shows photographs of the reactor and a section of the reactor. Oxygen from a bank of high pressure gas cylinders flows through two automatic control valves which divide the flow between primary and secondary streams and maintain the desired pressure level upstream of choke flow nozzles, thus determining the mass flow rates of primary and secondary oxygen. The primary oxygen is preheated and entrains coal particles which are fed to the primary stream from a high pressure, double-auger feeder. The primary stream, consisting of O_2 and entrained coal, enters the reactor through the 1.27 cm diameter inner pipe of a concentric-pipe, annular burner.

The secondary oxygen flows to another preheater, where it mixes with saturated steam from an electric boiler. The steam and oxygen mixture is further heated to the desired temperature and then fed through the outer concentric annular pipe. The gasification reactions take place downstream of the burner jet exit in the 20 cm. diameter, ceramic-lined reactor chamber. The 1.2 m long reactor chamber, shown schematically in Figure 2 consists of several segments of 15 and 30 cm lengths, one of which is the test probe section. By changing the order in which these segments are bolted together, the test probe section may be placed at 15 cm axial increments along the length of the reactor chamber.

After leaving the reactor, the hot reaction gases and char residue are cooled and the solids are scrubbed out of the gas phase with water in a packed scrubber. The cooled gas is vented and the scrubbing liquid is reduced in pressure and disposed of in the sewer drain.

TEST PROCEDURES AND MEASUREMENTS

The variables to be measured include temperature, pressure, and gas and particle compositions. Reactor temperatures are measured with either ceramic-shielded Platinum/Platinum-6% Rhodium thermocouples or suction pyrometers. Each reactor section has three thermocouple ports equally spaced around the inside wall of the ceramic liner, so that temperature variations in both the axial and angular directions can be measured. In addition, radial temperatures will be measured in the probe section. Reactor pressures are measured with transducers. Thermocouple ports can be used as pressure ports if desired, so that pressures can be measured at several axial and angular locations in the reactor.

Particulate and gas samples are obtained with water-cooled probes which are located in several radial positions in the test section. Similar probes have been used successfully in reacting flow measurements by this laboratory in earlier studies (1,2). The gas samples are analyzed using a gas chromatograph to determine concentrations of CO, CO_2, H_2, O_2, light hydrocarbons, and a gaseous tracer. The solid char sample is analyzed to determine ash, volatiles, sulfur and nitrogen content, together with other elements. The ash content of the coal is used as the solid phase tracer in order to determine the dispersion rates of the coal or char particles. Recent work (3), has indicated that some ash components may vaporize and decompose in the flame, and this problem is being considered.

The final piping and facility assembly is completed and facility check-out and cold flow tests have been conducted. Available results from several cold flow tests will be presented and discussed. From several cold-flow test results at atmospheric pressure, the following observations have been made: (1) the coal particles disperse much more slowly than the gases; (2) increasing the secondary velocity or the injection angle both significantly increase the rates of gas and particle dispersion; (3) reducing the particle size significantly increases particle dispersion rates. Additional test results will be given in the presentation. It is anticipated that some test data for reacting gasification tests will also be included in the presentation.

ENTRAINED GASIFIER MODEL

A computerized model for predicting characteristics of pulverized coal combustion and gasification uses the integrated or macroscopic form of the general conservation equations (4) for a volume element inside a gasifier or furnace, as illustrated in Figure 3. The following aspects of pulverized coal combustion have been included in the model: (1) mixing of primary and secondary streams; (2) recirculation of reacted products; (3) pyrolysis and swelling of coal; (4) oxidation of the char by oxygen, stream and carbon dioxide; (5) conductive heat transfer between the coal/char particles and gases; (6) variation in composition of inlet gases and solids; (7) variation in coal/char particle size; (8) oxidation of the hydrocrbons produced from coal pyrolysis; and (9) radiative heat transfer among the particles.

Key assumptions for this model are shown in Table 2, while differential mass, energy and momentum balances for particle and gas phases are summarized in Table 3. This set of first-order, non-linear equations also requires a large number of auxiliary, algebraic equations as component model parts. These equations describe the following aspects of the coal gasifier process: enthalpy-temperature relationships, physical properties including heat capacity, thermal conductivity, diffusivity, and viscosity; radiative interchange inside the gasifier; equations of state and mass flow continuity; convective and conductive heat interchange among the gases, particles and walls; rates of pyrolysis and oxidation of coal and char.

TABLE 2

Summary of Key Assumptions for Coal Model

1. Steady-state, compressible gas, with specified pressure variation.
2. Particles and gases in dynamic equilibrium.
3. Secondary gases and recirculated products input along reactor with instantaneous mixing.
4. Multiple particle sizes or types.
5. Particle phases and gas as separate phases.
6. Negligible gas conduction, diffusion, and thermal diffusion, gravity effects, particle interactions, wall friction, viscous dissipation, work on surroundings, gas phase radiation, particle-phase convective losses, kinetic energy.
7. Rate limiting steps include upstream radiation, gross oxidizer/fuel mixing, product recirculation, coal particle pyrolysis, char oxidation (with O_2, CO_2, H_2O).
8. Gas phase in local thermodynamic equilibrium.
9. Specified gas and particle ignition temperatures.
10. Coal pyrolysis by parallel activated processes.
11. Coal swelling proportional to extent of pyrolysis.
12. Spherical particles of uniform local particle temperature with specified char diameter and with internal and external reaction.
13. Irreversible particle reactions.
14. Ash inert and remains with the particle.
15. Moisture loss controlled by vapor diffusion.
16. Hydrocarbon volatiles produced from coal pyrolysis reactions, together with specified other chemical elements.
17. Char contains specified proportions of other elements which enter the gas phase at a rate proportional to the carbon reaction.
18. Char oxidation first order heterogeneous reaction, coupled with oxidizer diffusion to particle surface.

TABLE 3

Summary of Model Differential Equations

Type	Equation
Gas Element Continuity (k^{th})	$d(w_g\omega_k)/dx = A\sum_j r_{jk} + m_{sgk} + m_{\rho gk}$
j^{th} Particle Phase	$dw_j/dx = -Ar_j + m_{sj} + m_{\rho j}$
Gas Energy	$d(w_g h_g)/dx = h_{sg}m_{sg} + h_{\rho g}m_{\rho g} + A(\sum_j Q_j - Q_{cb} + \sum_j r_j h_{jg})$
Particle Energy (j^{th})	$d(w_j h_j)/dx = m_{sj}h_{sj} + m_{\rho j}h_{\rho j} + A(Q_{fj} - Q_{rb} - Q_j - r_j h_{jg})$
Gas Momentum	$d(w_g v)/dx + d(pA)/dx = m_s v_s + m_\rho v_\rho + vA\sum_j r_j$
Particle Number	$d(vn_j)/dx = (m_{\rho j}/\alpha_j A)$
Total Gas Continuity[1]	$d(w_g)/dx = A\sum_j r_j + m_{sg} + m_{\rho g}$
Coal Mass	$d(\alpha_{cj})/dx = -(r_{cj}/n_j v)$
Char Mass	$d(\alpha_{hj})/dx = -(r_{hj}/n_j v)$
Moisture Mass	$d(\alpha_{wj})/dx = -(r_{wj}/n_j v)$

1 Sum of Eqns 1 over k elements

A numerical solution has been developed for this entrained gasifier model. The model has been used to investigate effects of test variables on the extent of coal gasification and on the gas phase composition. Results indicate that the pyrolysis process is very fast and that oxygen in the gas phase is rapidly converted to CO_2. This is followed by the relatively slow CO_2-H_2O reactions with residual char. Specific predictive results will be presented in the paper and compared with available experimental results.

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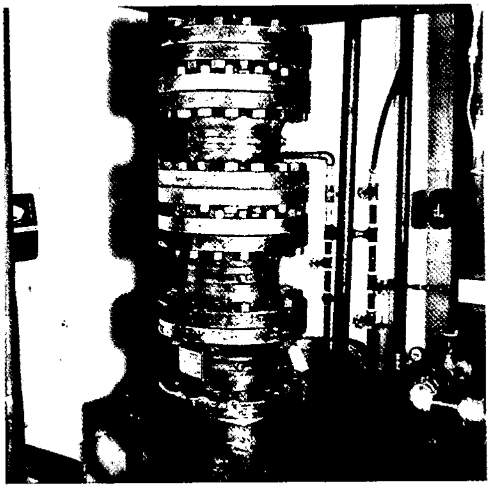
NOMENCLATURE

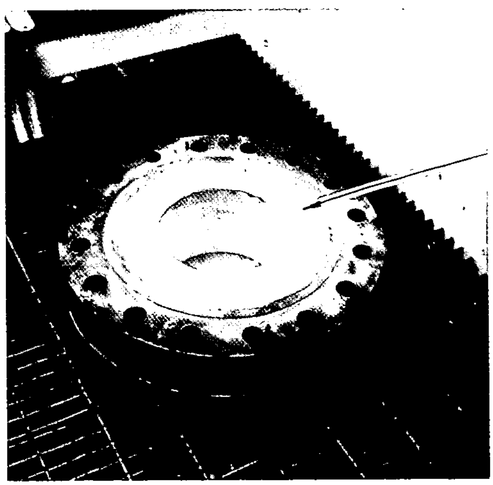
m_s	rate of secondary flow into control volume
w_g	rate of gas flow into control volume
w_j	rate of particle flow into control volume
m_ρ	rate of recirculation into control volume
Q_j	heat conduction between gas & particles
r_j	rate of pyrolysis and oxidation of coal/char
r_i	rate of reaction of gas species
Q_{cb}	rate of heat loss by convection
Q_{rb}	rate of heat loss by radiation
Q_{fj}	rate of radiative heat transfer in reactor
T_b	wall temperature
A	cross sectional flow area
w_k	mass fraction of k^{th} element
x	axial coordinate
h	static enthalpy
v	velocity
p	pressure
n_j	particle number density
α	mass of particle

Subscripts

g	gas
κ	k^{th} element
s	secondary
ρ	recirculation
j	j^{th} particle
c	coal
h	char
a	ash
w	moisture



High Pressure Reactor



Typical 6" Reactor Section

Figure . High Pressure Reactor and Typical Section.

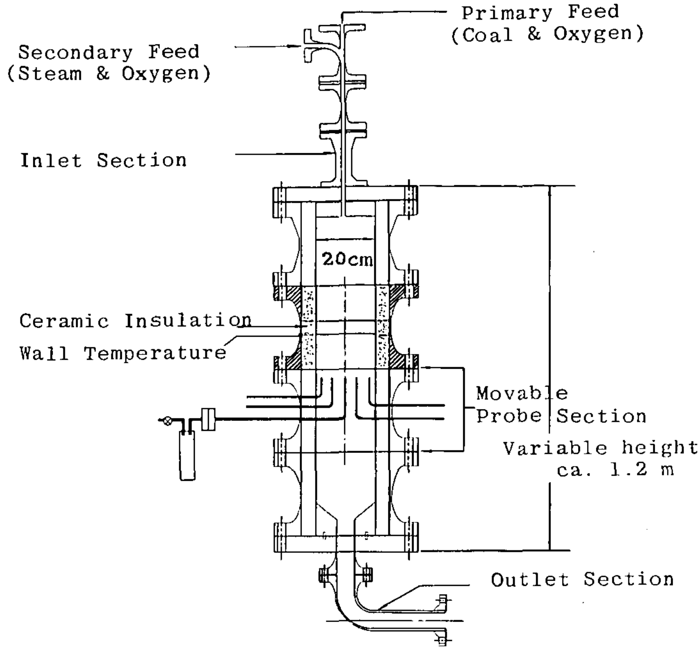


Figure 2. High Pressure Entrained Gasifier

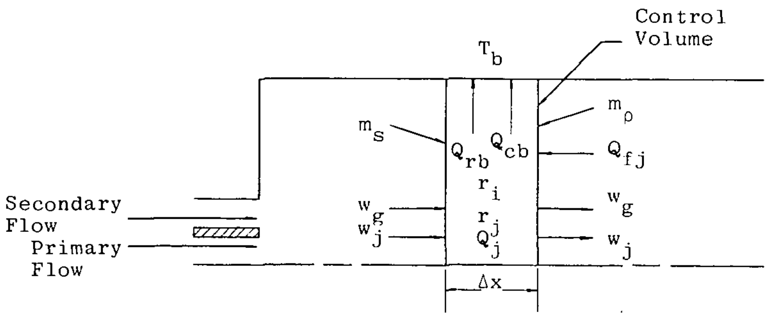


Figure 3. Schematic Diagram of Macroscopic Coal Gasification Model.